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Luminescence as Applied to Lighting

By H. G. JENKINS, M.Sc., F.Inst.P. *(Member)*, and A. H. McKEAG, M.Sc., A.R.I.C.

Summary

This paper deals with the main features of luminescence of interest to illuminating engineers. An account is given of the theoretical aspects of photoluminescence and the more important inorganic phosphors are mentioned. The factors which determine the luminous performance of both low and high pressure fluorescent lamps are discussed. Reference is made to a number of general matters concerned with luminescence, including the phenomena of electroluminescence.

(1) Introduction

The ordinary fluorescent lamp which has made the phenomenon of luminescence a common feature of our everyday life is, first and foremost, an electric discharge through low-pressure mercury vapour. The important feature about this form of discharge is that it emits radiation strongly in the ultra-violet; something like 50 per cent. of the total energy in the arc is radiated in a single line of wavelength 2,537 A and about 10 per cent. in a shorter wavelength line at 1,850 A. This at once accounts for the low luminous efficiency of the plain discharge and the high efficiency of the fluorescent lamp, in which a considerable fraction of the U.V. energy is transformed into light. The spectral quality of the fluorescent light, unlike that of the discharge itself, can be closely controlled and a wide range of colours and colour renderings can be obtained.

In the high pressure mercury vapour discharge, on the other hand, most of the energy is emitted in the visible region and only a few per cent. in the U.V., mainly in the region of 3,650 A. No appreciable gain in luminous efficiency can, therefore, be obtained by means of luminescence, but a worth-while improvement in colour rendering can be achieved, particularly with modern red-emitting phosphors, with little or no loss in efficiency.

The present paper discusses the main features of photoluminescence as applied in these lamps. Reference is made in a concluding section to a number of general matters, including fluorescent glass, luminescent materials excited by "black-glass" U.V. lamps, and the phenomenon of electroluminescence.

(2) Luminescent Powders (Phosphors)

The luminescent materials of chief concern in the present paper are the inorganic crystalline phosphors, of which zinc sulphide and zinc orthosilicate (willemite) are perhaps the best-known examples. The excitation band of sulphides is in the long-wave U.V. region 4,000-3,000 A while that of the silicate is in the short-wave U.V. region 3,000 A and below.

(2.1) Preparation

Sulphide phosphors are generally prepared by the usual chemical precipitation process. The precipitate is washed, mixed with fluxes such as magnesium chloride and the activator if required, dried and fired at about 1,150 deg. C for an hour or more to develop the crystalline structure which is an essential feature of inorganic phosphors.

Other types of phosphors are generally formed from a mixture of the component

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oxides, carbonates or other appropriate salts. The activator is added and the reaction occurs during the firing, which takes place at between 800 and 1,250 deg. C. for an hour or more according to the quantity involved and the nature of the compound.

All chemicals used must be of the highest purity to obtain the best efficiency and this is especially important with sulphide phosphors. The firing atmosphere depends on the nature of the compound and the state of valency of the activator in the finished phosphor. The phosphor as removed from the furnace is a lightly sintered mass which is reduced to a particle size of 1—5 microns by milling.

(2.2) The Activator

The luminescence of phosphors is usually associated with traces of specific impurities known as activators. Exceptions are zinc sulphide, calcium tungstate and magnesium tungstate, in which the activator is sometimes assumed to be due to a stoichiometric excess of zinc or tungsten atoms present in the crystalline lattice.

The luminous characteristics depend on the nature of the activator and the crystalline matrix in which it is dispersed. Because of the interaction between the activator and the matrix the same activator in different matrices can and does give rise to different luminescent colours. Some activators can exist in different valence states in different phosphors, which can give rise not only to a change in colour but also to modifications in the spectral structure of the emitted light. This makes it difficult to predict the luminous characteristics of any particular combination of activator and matrix.

The problem becomes even more complex if more than one activator is present. In the three examples of doubly activated phosphors given in Table 1, manganese when present alone gives practically no response to U.V., antimony when present alone in calcium halophosphate gives a blue fluorescence under 2,537 A U.V., while lead in calcium silicate and cerium in calcium orthophosphate give long-wave U.V. emission. When manganese is added it completely modifies the fluorescence, causing the colour of the halophosphate, for example, to change from blue through various shades of white to orange or pink according to the amount added. The mechanism by which the primary or sensitizing activators, antimony, lead and cerium, enable the manganese or secondary activator to function in these phosphors is obscure. It is significant that the luminescence due to the primary is always of shorter wavelength than that due to the secondary activator.

(2.3) Theoretical Aspects of Luminescence

The theoretical basis of the luminescence of inorganic phosphors has been fully discussed in a number of publications[1] and it is intended only to refer briefly to it in the present paper. According to the accepted theory, electrons are free to move in the crystal within certain energy bands and Fig. 1 shows the conventional energy diagram in which Band A represents the band filled with electrons when the crystal is unexcited. When the phosphor is excited by U.V. radiation some of the electrons are raised to an upper energy level represented by Band B. This is sometimes called the conduction band since excitation usually renders the crystal electrically conducting. The activator is pictured as introducing new energy levels in intermediate positions which may be unexcited or excited states c or c^1. So-called trapping levels, which may be due to crystal imperfections, may also be present close to the conduction band. Electrons trapped in these levels may be released into the conduction band by thermal energy and are responsible for the phosphorescent or afterglow emission from the phosphor.

When an electron is excited from the lower energy Band A to the conduction Band B by the absorption of U.V. energy, the net positive charge in Band A, sometimes called a positive hole, is assumed to behave like a positive electron and move about in the band until it is neutralised by an electron from the activator level. The

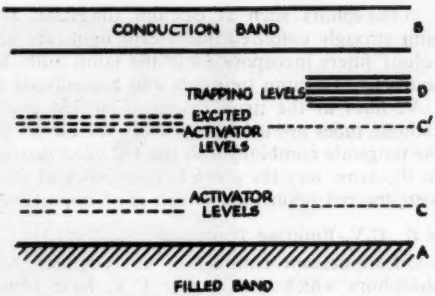

Fig. 1. Energy level system in impurity activated phosphors.

excited electron in the conduction band falls to the activator level replacing the electron which has just left, with emission of a quantum of fluorescent light. This two-step return process explains why the energy of the emitted quantum is always less than that of the absorbed quantum.

(3) General Characteristics of Phosphors

(3.1) The More Important Phosphors for Lighting

The phosphors of chief interest for fluorescent lamps are listed in Table 1, which gives their chemical formula, activator and luminescent colour. Zinc beryllium silicate which, in conjunction with magnesium tungstate, was used extensively during the first years of the fluorescent lamp, is not included in this list since it has been almost completely superseded by calcium halophosphate and calcium silicate phosphors. Magnesium tungstate is still widely used in certain white colours to supplement the blue, and cadmium borate the red, parts of the spectrum.

Table 1

The More Important Short-Wave U.V.-Excited Phosphors

Matrix*	Chemical formula	Activator (S)	Colour of fluorescence under 2537 A radiation
Calcium tungstate	$CaWO_4$	—	Blue
Magnesium tungstate	$MgWO_4$	—	Blue-white
Barium silicate(2)	$BaSiO_3$ to $Ba_2Si_3O_8$	Pb	Blue to blue-green
Sodium barium silicate(2) ...	$Na_2Ba_2Si_3O_9$	Pb	Blue to pale blue
Barium titanium phosphate(4) ...	$Ba_2P_2O_7$	Ti	Blue-white
Zinc orthosilicate	Zn_2SiO_4	Mn	Green
Calcium halophosphate(5) ...	$3Ca_3(PO_4)_2.Ca(F,Cl)_2$	Sb Mn	Blue to yellow or orange, including various white colours
Calcium silicate(6)	$CaSiO_3$	Pb Mn	Yellow to orange-red
Cadmium chlorophosphate ...	$3Cd_3(PO_4)_2.CdCl_2$	Mn	Orange
Cadmium borate	$Cd_2B_2O_5$	Mn	Orange-red
Calcium orthophosphate(7) ...	$Ca_3(PO_4)_2$	Ce Mn	Red
Magnesium arsenate(8)	$Mg_{10}As_2O_{15}$	Mn	Red
Magnesium fluogermanate(9) ...	$Mg_4GeO_6MgF_2$	Mn	Red

* Literature references to more recent phosphors indicated by bracketed numbers

Phosphors such as calcium tungstate, zinc silicate and cadmium borate, which emit strongly coloured fluorescent light, are also used, sometimes in conjunction with colour filters incorporated in the lamp bulb, to provide blue, green and red coloured sources. Calcium tungstate and zinc silicate are excited by the very short wavelength U.V. lines in the neon discharge at 736 and 740 A ([10]), and neon fluorescent cold cathode tubes are used extensively for advertising signs. The blue luminescence from the tungstate combines with the red neon discharge light to give a subjective pink colour. In the same way the green luminescence of the silicate gives a gold colour when mixed with the red neon light which is of importance in high-voltage lighting([11]).

(3.2) U.V.-Emitting Phosphors

Luminescent emission is not confined to the visible part of the spectrum and phosphors which emit in the U.V. have found application as sources of long-wave U.V. for display and photoprinting purposes, the former in conjunction with Nickel or Wood's glass filters; others of somewhat shorter-wave U.V. emission are used for erythemal applications. Table 2 gives particulars of the more important U.V.-emitting phosphors.

Table 2
U.V.-Emitting Phosphors

Matrix	Activator	Peak of the emission
		A
Calcium phosphate([12])	Tl	3,250
Calcium phosphate([12])	Ce	3,650
Barium disilicate([13])	Pb	3,500
Calcium zinc phosphate([14]) ...	Tl	3,120

The colour of lamps coated with these phosphors is bluish and the luminosity is low, being very similar to that of the plain mercury discharge.

(3.3) Excitation and Emission Characteristics

Most of the phosphors in Table 1 are excited strongly by the U.V. mercury line at 2,537 A. The excitation bands, like the emission bands, cover a considerable range of wavelengths. Thus some of the phosphors are excited by U.V. of wavelengths longer than 3,000 A and shorter than 2,000 A. The excitation band of willemite and calcium tungstate is known to extend over the enormous range from 3,000 A down to the wavelength of the neon resonance line at 740 A.

The emission spectra of most phosphors also cover a wide range of wavelengths, as may be seen from Fig. 2, which shows typical spectra. A few phosphors show some evidence of structure in emission spectra, examples of which are shown in Fig. 2 (f) and (g). In these the electronic transition responsible for the emission is thought to occur in inner electron shells of the activator atom or is otherwise screened from the effects of the surrounding matrix atoms.

Spectral emission curves of the main phosphors of interest for lighting are given in Fig. 3. To obtain these curves the fluorescent light from the phosphor is focused on the slit of a monochromatic illuminator which is a fixed-arm spectrometer with a second slit in place of the eyepiece. The dispersed light passing through the outlet slit is measured wavelength by wavelength on a photoelectric multiplier cell. The instrument is calibrated by replacing the fluorescent source by a tungsten filament lamp operating at a known colour temperature.

In general, if more than one activator is present the contribution of each activator may be detected in the curve, and the shape of the curve can be varied by varying the proportions of the activators. The resultant spectral emission curve of a mixture of a

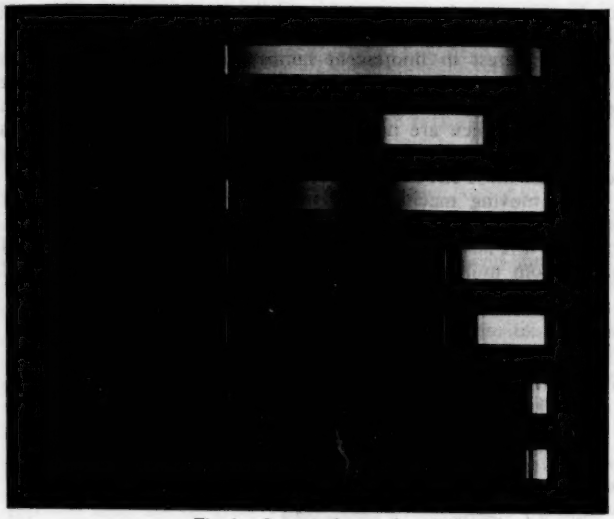

Fig. 2. Spectra of some short U.V. excited phosphors.

number of phosphors is determined by adding their separate curves together in the proportions present in the mixture.

(3.4) Phosphorescence

Phosphorescence is the persistence of light emission after the excitation has stopped. Some sulphide phosphors continue to glow for many hours or even days after excitation, the intensity of the glow decaying according to a hyperbolic law. Most of the phosphors of interest for fluorescent lamps show fairly strong phosphorescence for

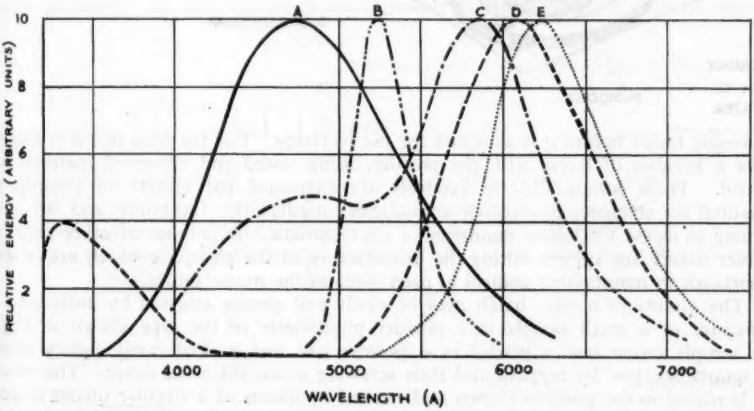

Fig. 3. Spectral energy curves of short U.V. excited phosphors. A, magnesium tungstate; B, zinc orthosilicate; C, calcium halophosphate (daylight); D, calcium metasilicate; E, cadmium borate.

a fraction of a second after stopping the excitation, the decay tending to be exponential rather than hyperbolic.

Phosphorescence is of interest in fluorescent lamps operating on a.c. supplies because the persistence of the light emission during the fraction of the cycle when the discharge current is zero helps to reduce stroboscopic flicker. It is curious that, with one or two notable exceptions which are not of importance for lighting, phosphors showing strong blue phosphorescence are not known. This explains why cold white fluorescent lamps tend to show more stroboscopic flicker than do warm white lamps.

Except possibly where moving machinery is involved, the stroboscopic flicker obtained with fluorescent lamps on ordinary 50-cycle supplies is of no consequence. Where flicker is troublesome it is advisable to use the mixed light from lamps operated on split-phase circuits or from multi-phase supplies, to reduce or eliminate residual flicker.

(3.5) Testing Phosphors

(3.5.1) *Physical Tests*

Fluorescent lamp performance is greatly dependent on the quality of the phosphors used. To secure the necessary high quality and uniformity, each batch of phosphor is

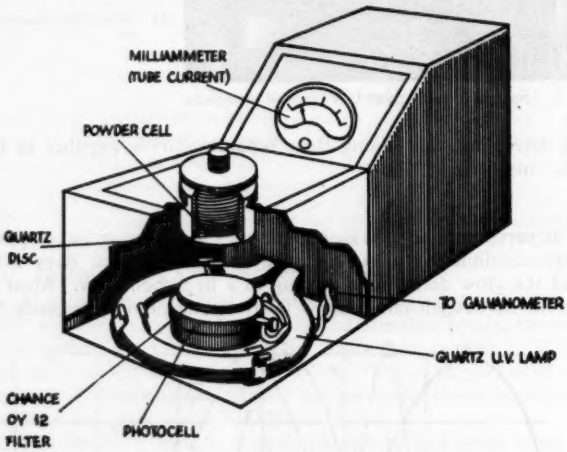

Fig. 4. Powder photometer for measurement of luminance of phosphor samples.

rigorously tested before it is accepted for use in lamps. For the final test it is usual to make a number of lamps with the powder, using tested and approved material as a control. These lamps and the controls are examined for quality of coating and measured for efficiency and colour appearance, usually after 100 hours' and 500 hours' burning to assess the lumen maintenance characteristic. A number of other tests of a simpler nature are applied during the manufacture of the phosphor which are of great importance in maintaining control at each stage in the manufacture.

The quality of a pilot batch may be easily and simply assessed by measuring the luminance of a small sample in a powder photometer of the type shown in Fig. 4. The sample under test is placed in a powder cell and packed fairly tightly against the quartz window by tapping and then screwing down the back cover. The powder cell is placed in the position shown and excited by means of a circular quartz mercury discharge tube arranged below and around a photoelectric cell so that no direct radiation from the discharge tube reaches the photocell. The latter measures the fluorescent and reflected light from the specimen under test. The contribution of the

discharge radiation reflected by the specimen is measured by using a similar powder cell filled with a white inert powder such as magnesium oxide. This test is usually repeated on a further specimen which has been subjected to a standard milling schedule in an organic liquid such as butyl acetate, which gives a measure of the resistance of the powder to the suspension-making process.

Additional factors which influence the performance of phosphors in lamps include particle size and density. These characteristics determine the quality of the coating and the coating weight necessary to achieve the optimum covering of the tube as discussed in Section (4.3).

Particle size and density are often measured as a routine on batches of phosphor. The former may be measured by microscopic techniques or by other well-known methods. A useful routine control test which gives an overall value of the specific surface of the powder is based on the Carmen permeability method[15]. In this test the pressure drop across a standard bed of powder is measured whilst a measured flow of gas is passing through the bed. The mean diameter of the powder particles can be derived from the value of the specific surface thus determined.

Measurements of true and bulk density of the powder can be made by established methods and are indicative of the constancy of the product.

(3.5.2) *Chemical Tests*

In addition to physical tests, chemical analysis of starting materials and the finished product are usually made. Besides conventional chemical methods, spectrochemical tests are of great value for determining the presence of trace elements and adventitious impurities. X-ray analysis provides an invaluable method of following the course of chemical reactions in the matrix itself and, in the early stages of phosphor development, of determining the crystalline nature of the powder.

(4) The Fluorescent Lamp

(4.1) Emission and Utilisation of U.V. Radiation

It is, perhaps, desirable to give some consideration to the factors influencing the emission and utilisation of U.V. in the discharge. Fig. 5 shows a simplified form of the conventional energy level diagram of the neutral mercury atom. The vertical scale represents the excitation energies in electron volt units. An electron volt is the energy gained by an electron when accelerated through an electric field of one volt

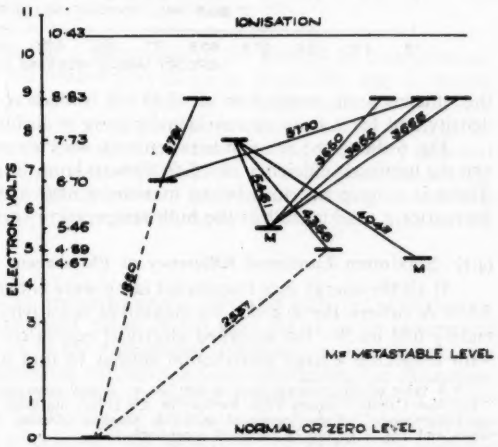

Fig. 5. Energy transitions of the neutral mercury atom. (Wavelengths in Angstrom units).

potential difference. The outermost electrons of the mercury atoms absorb energy in the discharge, and the horizontal lines represent their possible energy states. An electron excited to the 10.34-volt level is removed from the atom, and this is known as the first ionisation potential of mercury. The characteristic lines in the mercury spectrum are emitted when an electron changes from an upper to a lower level as shown in the diagram. It will be noted that the important U.V. line at 2,537 A is due to an electron transition between the first excited level at 4.89 volts and the zero level. Normal unexcited mercury atoms absorb 2,537 A radiation strongly and are as a result excited to the 4.89 level.

A quantum of 2,537 A radiation in a fluorescent lamp can be absorbed and re-emitted many times before it reaches the fluorescent coating. This process increases the effective time spent by the electron in the 4.89-volt level, and with it the probability that it will be excited to one of the higher levels from which it can escape only by the emission of a line in the visible spectrum. The number of times the quantum is absorbed and re-emitted depends on the concentration of mercury atoms in the discharge or, in other words, on the pressure of the mercury vapour.

Increasing the tube current above a certain optimum value also increases the probability that electrons in 4.86 levels will be excited to higher levels by providing a higher electron concentration in the discharge. Thus both high mercury vapour pressure and high tube current are unfavourable for the production of 2,537 A radiation and hence for the excitation of luminescence. For a fixed mercury vapour pressure

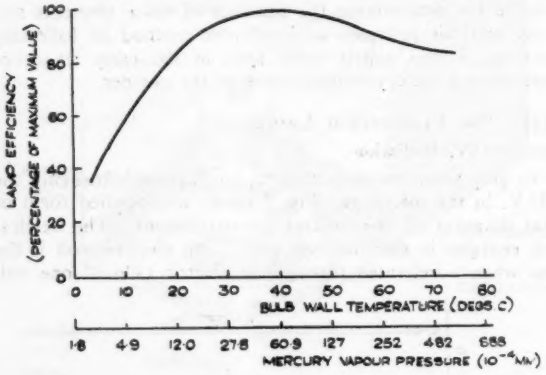

Fig. 6. Effect of mercury vapour pressure on the efficiency of 80-watt fluorescent lamps.

the efficiency of production of 2,537 A radiation increases with decreasing current density and for a fixed current density there is an optimum mercury vapour pressure.

Fig. 6 shows the relation between bulb wall temperature or mercury vapour pressure and the luminous efficiency of a 5-ft. 80-watt lamp burning in free air without draughts. There is a steep rise to a broad maximum near a wall temperature of 40 deg. C. and thereafter a gradual fall as the bulb temperature further increases.

(4.2) Maximum Luminous Efficiency of Fluorescent Lamps

If all the energy in a fluorescent lamp were converted into green light of wavelength 5,550 A (where the eye has its maximum sensitivity) the efficiency would be approximately 620 lm./w., the so-called electrical equivalent of light*. If the light were white with a spectral energy distribution similar to that of daylight, the efficiency would be

* A value of this constant close to 680 lm./w. is now generally accepted. See, for example, de Groot, W., "The New Candle," Philips Tech. Review, **10**, 150 (1948) and Stiles, W. S., "The Eye, Brightness and Illuminating Engineering." (Paper presented at I.E.S. Summer Meeting, Eastbourne, May 20-23, 1952.) The above values and Fig. 8 should be modified accordingly.

230 lm./w. As mentioned in Section (1) the U.V. energy in the positive column of a low-pressure mercury discharge is about 60 per cent. of the total energy in the lamp, which reduces the above figure to 140 lm./w. There is a transformation loss of nearly 50 per cent. in changing a quantum of 2,537 A radiation into light of wavelength 5,000 A in the middle of the visible spectrum. There is a further loss due to the fact that the ratio of the number of quanta of U.V. absorbed by the phosphor to the number of fluorescent quanta emitted is less than unity. This is known as the quantum efficiency of the phosphor and may be taken as between 80 and 90 per cent. Making allowance for these losses the value of the maximum efficiency to be expected from a fluorescent

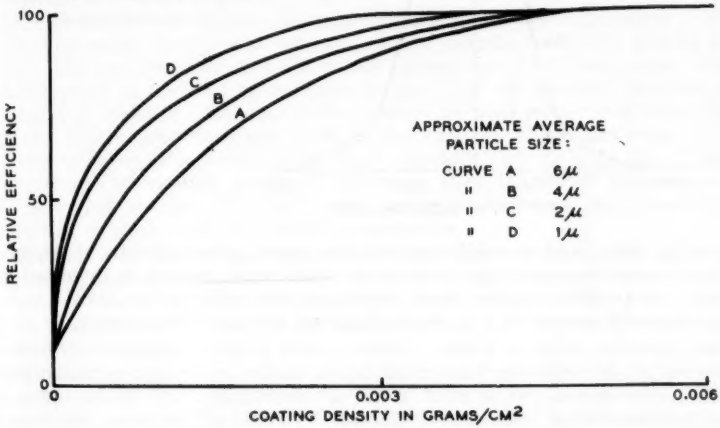

Fig. 7. Relation between particle size, coating density and luminous efficiency of a halophosphate phosphor.

lamp giving white light of daylight quality is 60 lm./w. This does not include the contribution of the visible line radiation from the discharge itself, which adds a further 5 lm./w. to the efficiency.

(4.3) The Fluorescent Coating

The fluorescent coating is applied as a suspension of the powder in nitrocellulose, which is later removed by baking the coated tube in air to about 450 deg. C. before the lamp is processed. The particle size of the powder and the coating density are adjusted to give the maximum utilisation of U.V. with a minimum loss of light by absorption. In general the finer the particle size the lower the coating density required to obtain the optimum efficiency. Care must be taken not to over-grind the powder since this reduces its efficiency. The relation between particle size, coating density and luminous efficiency is shown in Fig. 7 for a halophosphate of the type used in the daylight colour lamp.

(4.4) Colour and Colour Rendering

By controlling the mercury vapour pressure and the current density in the discharge, the emitted radiation can be concentrated either in the ultra-violet, as in fluorescent lamps, or in the visible spectrum, as in the high-pressure mercury vapour lamps. In both types of lamp the resultant luminous efficiency is about the same; the important characteristic of the fluorescent lamp is that its visible emission consists of broad spectral bands of fluorescent light, the luminosity or energy distribution of which can be controlled to give a wide range of colours. The light from a high-pressure mercury

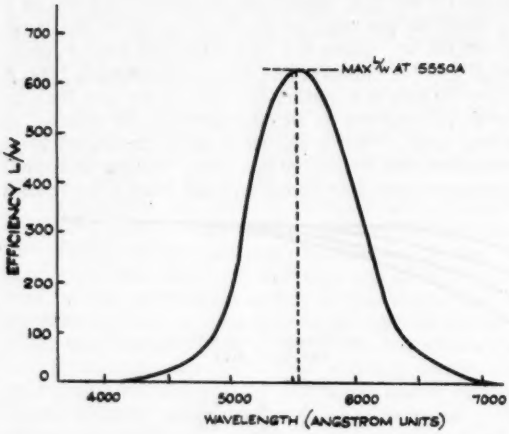

Fig. 8. Relation between wavelength (or colour) and efficiency.

lamp, on the other hand, is mainly line radiation which is characteristic of the mercury atoms and cannot be controlled to any worth-while extent. As will be discussed below, however, it is possible to effect some control of the colour of an HPMV lamp by utilising the small amount of U.V. in the discharge to excite luminescence.

The phosphors listed in Table 1 enable a wide range of spectral distributions to be obtained. If the red content of a phosphor is insufficient for any particular purpose a suitable proportion of one or other of the red-emitting powders can be added in the coating suspension to give the desired adjustment. If the efficiencies of the constituent powders in a blend are separately known, the efficiency of a lamp using the blend can

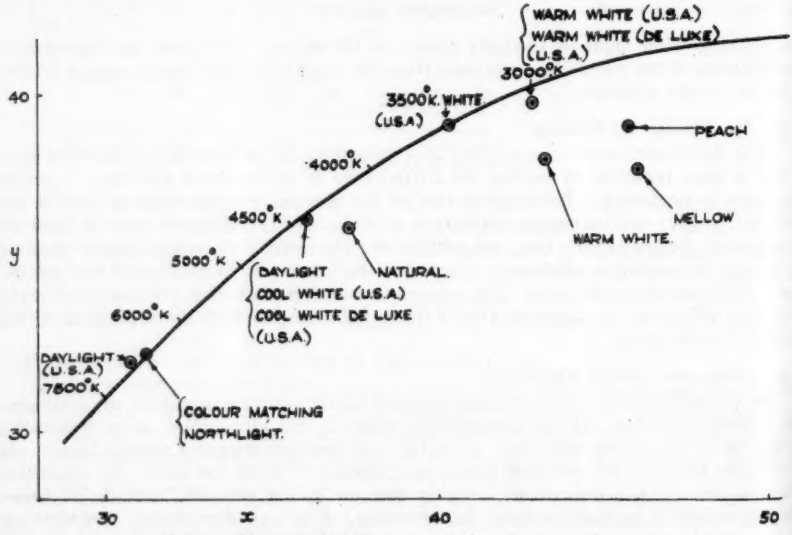

Fig. 9. Chromaticity co-ordinates of white fluorescent lamps.

be calculated very simply for the same type of lamp from the known proportions of the constituents.

Efficiency and spectral distribution of a fluorescent lamp are closely related and any increase in the emission at the red or blue ends of the spectrum can only be obtained by accepting a reduced efficiency. The curve in Fig. 8 shows the relationship between wavelength of light and luminous efficiency. The ordinates represent the maximum lumens theoretically obtainable from one watt of energy. The curve, which is identical with the well-known average eye sensitivity curve, can be used to determine the relative efficiencies to be expected from different phosphors whose spectral energy curves are known.

It is proposed only to mention the measurement of the important colour characteristics of fluorescent lamps, since the subject has recently been fully treated elsewhere [16]. The two characteristics are colour appearance of the lamp when alight, which is expressed in terms of co-ordinates in the C.I.E. chromaticity diagram, and colour rendering, which is measured in this country by the luminance in eight bands covering the visible spectrum from 3,800 A to 7,600 A. The luminance of the mercury line radiation is included in the band in which the line lies. Fig. 9 shows the approximate chromaticity points of the main white fluorescent lamps now in use both here and abroad. The full black line is the locus of the chromaticity co-ordinates of a black body at various temperatures.

An alternative method of expressing the spectral composition of the light from the lamp, much used abroad, is by means of spectral energy curves similar to those discussed above for the powders themselves but which include a strip about 100 A wide in the positions of each mercury line and of an area corresponding to the energy contribution of the line.

It is interesting to compare the white fluorescent lamp colours which have evolved in this country and in the United States. In Table 3 are listed the main white colours marketed in each country, together with the colour temperature of the nearest point on the full radiator curve as estimated from Fig. 9.

Table 3

Comparison of British and United States White Colours

	Great Britain	Nearest point on full radiator curve to colour co-ordinates	United States	Nearest point on full radiator curve to colour co-ordinates
		deg. K		deg. K
1	Colour Matching	6,500	Daylight	6,700
2	Daylight	4,500	Cool White	4,500
3	Natural	4,200*	Cool White de Luxe	4,200
4	Warm White	3,300*	Warm White	3,200
5	Mellow	2,700*	Warm White de Luxe	3,200

* Appreciably below the full radiator curve.

In each country the range comprises: (1) A special purpose white colour for colour matching and similar uses which is a fairly close match to the light from an overcast north sky; (2) A colour for general lighting where high efficiency is combined with reasonable colour rendering; (3) A similar colour giving improved colour rendering in the red region at a somewhat reduced efficiency; (4) A warmer colour than (3) of high efficiency; and (5) a warm colour giving better rendering of the complexion and of foodstuffs at a reduced efficiency. The similarities in these trends are, perhaps, more remarkable than the differences.

(4.5) Lumen Maintenance

When comparing the luminous efficiency of fluorescent lamps, not only must the dimensions and ratings of the lamps be taken into account, but also the spectral quality of the light emitted and the efficiency maintenance throughout the life of the lamp. A characteristic of the fluorescent lamp is the fairly rapid fall in light output during the first 100 hours of life and thereafter at a much lower rate. The phenomenon has been extensively studied, and much is now known about the effect of phosphor composition, lamp processing and the cathode emissive coating products on light depreciation. Nevertheless, it cannot be claimed that the precise mechanism of the residual causes is fully understood.

There is no doubt that a major cause of the fall in light output from the lamps is interaction between excited mercury atoms in the discharge and the phosphor crystals. It has been shown that the depreciation can take place outside the discharge if the phosphor is in contact with mercury atoms excited by mercury resonance radiation (17). The effects of the mercury discharge on the phosphor are partly physical and partly chemical. The physical effect is caused by a film of mercury or its compounds forming on the fluorescent layer and preventing the U.V. radiation from reaching it. This film can be removed by heating, but tends to re-form rapidly, which suggests that the nuclei upon which the mercury condenses are unaffected by the heat treatment. The chemical effect is probably due to attack of the powder by excited mercury atoms with consequent change in the matrix composition or the activator. It has been suggested, for example, that in certain phosphors the manganese can be reduced from the tetravalent to the divalent state, rendering it inoperative as

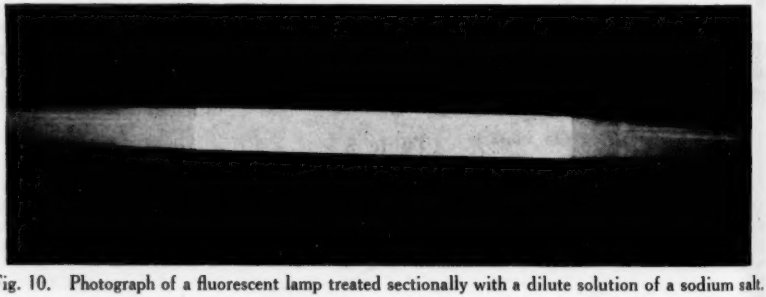

Fig. 10. Photograph of a fluorescent lamp treated sectionally with a dilute solution of a sodium salt.

an activator in that particular matrix. It is not unknown for coloured decomposition products of the phosphor to be formed under the action of the discharge by chemical reduction processes.

The marked effect of conditions at the glass-phosphor interface on lumen maintenance has been demonstrated(18). In particular, free alkali on the glass surface can act as nuclei for the mercury atoms, and improvements in lumen maintenance result from special glass-washing treatments to remove surface alkali. Free alkali in the phosphor itself can have a similar effect. Fig. 10 is a photograph of a section of a fluorescent lamp bulb, part of the coating of which has been treated with a dilute solution of a sodium salt. Marked blackening of the treated coating has taken place after 100 hours' burning.

There is some evidence to show that in certain phosphors the excited mercury atoms react with superficial lattice oxygen atoms with unsatisfied bonds, to form fairly stable chemical compounds which are not decomposed below the melting point of the glass tube(17). There is little doubt that the exceptionally good lumen maintenance

which is a characteristic of halophosphates is due to their high chemical stability and freedom from traces of alkali. The small amounts of free antimony trioxide present in halophosphates probably inhibits attack by mercury atoms, as has more recently been shown in zinc orthosilicate[19]. A number of other inhibitors are known, some of which are specific to certain phosphors.

(5) H.P.M.V. Fluorescent Lamps

In the H.P.M.V. fluorescent lamp the phosphor is applied not on the discharge envelope but on an enlarged outer envelope to keep its temperature down to a reasonable value. Using a copper activated zinc cadmium sulphide, the peak emission of which is in the orange-red region, a worthwhile increase in the red content of the light is obtained. Thus in the 400-watt lamp the red ratio (percentage of total lumens passing a Wratten No. 25 filter) is increased from about 1½ per cent. to 4½ per cent. by means of fluorescence without any change in the efficiency. Lamps of this type have been used in this country for many years. Because of phosphor limitations, the utilisation of available U.V. energy is not very good in this lamp and the self colour of the phosphor crystals makes the resultant colour of the light somewhat yellow.

The development of the new red phosphors, magnesium arsenate, magnesium germanate (listed in Table I), and a new alkaline earth silicate phosphor[20] has made available a range of phosphors more suited to the H.P.M.V. fluorescent lamp. Red ratios approximately double those given by the old phosphors are possible, and because self colour in the phosphors is small the colour appearance of the lamp is much whiter.

It is of interest to estimate the performance to be expected from H.P.M.V. fluorescent lamps using the new phosphors. Approximately 4 per cent. of the energy of an H.P.M.V. lamp is emitted in the U.V. at 3,560 A. If the U.V. energy in, say, the 125-watt lamp amounts to 5 watts and is transformed into red light of wavelength 6,500 A, which is near to the peak of the emission curves of the new red phosphors, the lumens of red light amount to $5 \times 150 \times \frac{3,650}{6,500} \times 0.8$ or 340 lumens. Here 150 is the theoretical efficiency of light of wavelength 6,500 A obtained from the curve in Fig. 8. The fraction $\frac{3,650}{6,500}$ is the transformation efficiency of the process and 0.8 the quantum efficiency of the phosphor as explained earlier. If the total lumens emitted by the lamp amount to 5,000 (40 lm./w.) the percentage of red light from the phosphor is 6.8 per cent. Adding the red ratio of the H.P.M.V. discharge, which amounts to 1.7 per cent., it is seen that a red ratio of 8.5 per cent. at an efficiency of 40 lm./w. from the new lamp is not an unreasonable expectation. The initial performance of a glass H.P.M.V. lamp might be expected to be somewhat poorer than this because of some loss of U.V. by absorption in the glass walls of the discharge tube and also because the red ratio of the discharge itself is lower than in the quartz lamp. Preliminary measurements on quartz types using one or other of the new red phosphors have given results reasonably close to the theoretically estimated values. Glass lamps have given red ratios about 2 per cent. lower.

Fluorescent lamps using germanate and arsenate phosphors have recently been marketed in the United States and on the Continent. The particular phosphor which will finally be used in this country will be determined from the results of extended tests and a study of economic and other considerations.

(6) General

(6.1) Fluorescent Glass

Luminescent effects in glass have probably been observed since the experiments of Hauksbee at the beginning of the eighteenth century. Glass made specifically to

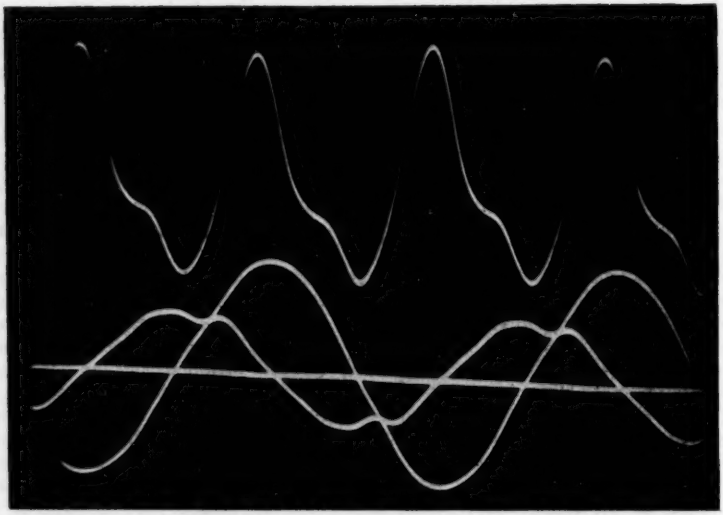

Fig. 11. Waveforms of applied voltage (B), current (C), and light output (A), for a typical luminous capacitor.

show fluorescence under U.V. excitation is, however, a comparatively recent development.

As might be expected from the complex structure of glass, this luminescence is even less understood than that in crystalline materials. The luminescent centres, corresponding to the activator in inorganic phosphors, may be made of ionised molecules such as uranium dioxide or co-valent molecules such as cadmium sulphide, or neutral atoms such as silver, lead or tin, or the luminescence may be due to crystalline materials such as zinc silicate formed in the glassy surround. This gives an opalescent effect due to the presence of undissolved crystalline material.

Uranium glass has found wide application for neon signs. Glasses containing tin and other neutral metallic activators are not satisfactory unless the iron content is very low. Before the war a number of glasses of this type were available[21], but because of the extreme purity of the glass the cost was high. For this reason the glasses were generally used in the form of thin internal flashings on a normal glass which was sometimes coloured to increase the range of resultant colours. Efficiencies were about half those obtained with normal phosphors, and apart from a limited use for neon signs such glasses have not come into widespread use.

(6.2) Luminescent Material for Display Purposes

Most people have seen the striking colour effects obtained when certain types of luminescent materials are excited by filtered long-wave U.V. radiation in the absence of extraneous light. Paints made from sulphide phosphors are available in a range of colours which, when used in conjunction with black glass lamps, can give lighting effects of great beauty and artistic merit. As with ordinary paints, the range of shades and colours available can be greatly extended by mixing the fluorescent powders. Mixtures of normal paints or pigments, however, give subtractive mixtures of colours, while mixtures of fluorescent powders give additive mixtures of coloured lights. Thus, a yellow pigment is yellow because it absorbs blue and a mixture of blue and yellow paints gives green because they absorb red and

blue light respectively from the incident light. An artist using fluorescent powders as pigments has to remember that a mixture of blue and yellow no longer gives green, but white, fluorescent light.

During the last war both inorganic and organic fluorescent materials found many applications for such purposes as instrument lighting, black-out indicators, signalling devices and the like. More recently, lacquers containing fluorescent dyes have been widely used for advertising.

Instrument lighting on aircraft is a somewhat special lighting problem as the pilot is working under conditions of scotopic vision when the periphery of the retina is particularly sensitive to blue and green light. Such colours, even at luminance levels too low for the normal eye to function, produce in the dark-adapted eye a feeling of discomfort analogous to that produced by glare in the normal eye. For this reason the practice of using fluorescent colours towards the red end of the spectrum for instrument lighting is now general. In this country a special yellow phosphor with narrow band emission containing no green light has been widely used[22].

Most organic fluorescent dyes are not excited unless the molecules of the dye are highly dispersed in a suitable solvent or on fibres of fabrics or in resins which serve to isolate the molecules from each other. Fluorescent dyed resins can be reduced to fine powders when dry and the powder, suspended in a suitable medium, applied to surfaces by painting, spraying or one of the established printing processes. Excited by normal daylight, the fluorescent emission adds to the coloured reflected light from the lacquer to give brilliant coloured effects in daylight. Unfortunately, with one or two notable exceptions, organic fluorescent dyes are very fugitive and fading is a serious problem.

Two interesting applications of organic fluorescent substances used in conjunction with black glass lamps are worth mentioning. The first is to the detection of fine

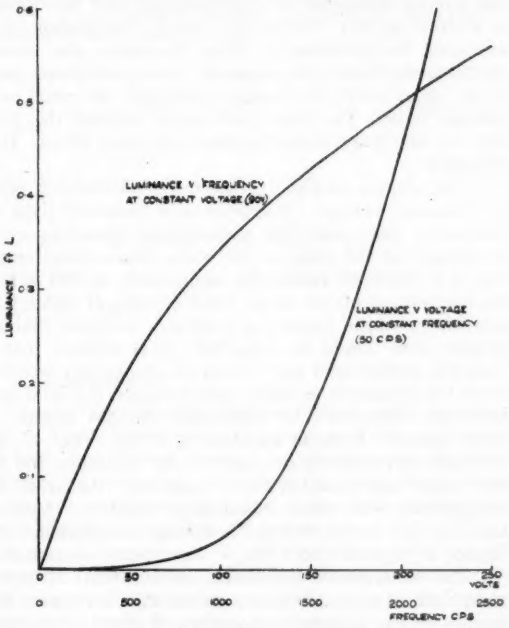

Fig. 12. Relationship between voltage, frequency and electroluminescent output.

cracks in metals, particularly in non-ferrous metals where the colloidal iron and powerful magnetic field method cannot be used[23]. The metal part is treated with a strongly fluorescent substance such as anthracene, by applying a solution of anthracene in trichlorethylene, and after removal of the excess anthracene the cracks show as fine bright lines when irradiated by U.V. from the black glass lamp.

In the second application a colourless organic compound is used which is absorbed on fabrics but which shows only under the action of U.V. The material is used to mark linen in laundries and sorting is done by the aid of black glass lamps.

(6.3) Electroluminescence

Electroluminescence is the excitation of phosphors in a varying electric field. The phenomenon was discovered in 1936[24] but recent work in the United States[25] has brought it to the attention of illuminating engineers. The discovery of the phenomenon arose out of an earlier observation[26] that the phosphorescent decay of certain phosphors previously excited by U.V. radiation could be accelerated in an electric field. An analogous phenomenon is the well-known excitation of certain crystalline substances, for example pure carborundum, by the passage through them of an electric current[27].

A convenient method of producing electroluminescence is to incorporate the phosphor in the dielectric of a simple capacitor, one of the plates of which comprises a transparent conducting film on a sheet of glass and the other a thin metallic film, the plates being spaced about 0.1 mm. apart. With 200 volts 50 cycles applied to the plates, giving a field strength of about 20,000 volts per cm., the phosphor glows with its characteristic colour. If the voltage is increased beyond a certain value, which depends on the way in which the luminous capacitor has been constructed, breakdown will occur. Increasing the frequency of the applied voltage also increases the energy dissipated in the phosphor and therefore the brightness of the glow. It is interesting that the spectral energy distribution of the light is modified slightly by changing the frequency. Fig. 11 shows the wave forms of the applied voltage, current and light output for a typical luminous capacitor. The light output curve is in phase with the voltage although its peak occurs slightly in advance of the voltage peak. The phase difference between the peaks is to some extent dependent on the activator content, which in turn affects the electrical conductivity of the phosphor.

The curves in Fig. 12 show the relationship between light output and frequency at constant voltage (90 volts) and between light output and voltage at constant frequency (50 cycles) for a particular phosphor giving a green luminescence. The luminance of the plate at 200 volts 2,000 cycles measured on a Macbeth photometer was 8 ft.-lamberts and on the same plate at 200 volts 50 cycles about 0.5 ft.-lamberts. At luminances of the latter order an area of about 1,200 sq. ft. would be required to provide the same lumens as a 60-watt tungsten filament lamp; for white light a much greater area would be required. It is evident that at power frequencies very high voltages would need to be used to obtain any worth-while light output. Quite apart from the objection to using such voltages, it would appear that the problem of making luminous capacitors to withstand voltages greater than about 1 kilovolt has yet to be solved. Even at frequencies of the order of 400 cycles, such as are sometimes available for lighting an aircraft, for example, the light output is insufficient except for rather specialised forms of lighting. Accurate luminous efficiency measurements are difficult with electroluminescent sources. Measurements made on the phosphor used for the curves in Fig. 12 indicate an efficiency of the order of 2 or 3 lm./w. but figures as high as 6 to 8 lm./w. have been mentioned.

No satisfactory theoretical explanation of electro-luminescent phenomena has been forthcoming. It seems reasonable to expect that any such theory should conform with the accepted mechanism of photoluminescence or suggest an equally accept-

able one. In addition it must account for the exponential relationship between light output and field intensity, the absence of phosphorescence, the relation between temperature and light output and the relation between light output and activator content and matrix composition. In the absence of any real understanding of the phenomenon it is not possible to estimate the order of the efficiency which might be realised from electroluminescence in the future. One or two experimental ceiling lighting installations have been made in the United States but nothing appears to have happened so far to suggest that this interesting phenomenon will revolutionise lighting.

The maintenance of light output of electroluminescence is markedly worse than in conventional fluorescent lamps and the factors which contribute to the fall in light output are even more obscure. An understanding of the mechanism of electroluminescence is necessary before the factors contributing to this depreciation can be evaluated.

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Discussion

MR. H. R. RUFF: Among the excellent lecture demonstrations, that showing fluorescence excited by a black light U.V. phosphor lamp did not seem to me to indicate the efficiency of obtaining "black light" in this way. Do the authors agree with our data that the efficiency of such lamps for this work is between two and three times that of the normal high-pressure mercury vapour black lamps? The latter are higher brightness sources more suitable for obtaining concentrated beams.

In the wide field covered by the paper there should be points of interest for everyone. The authors still seem somewhat troubled by the question of what is the "colour" of the lamp. By strict definition this is probably the subjective appearance of the lamp, but owing to the fact that it is the colour rendering property of a light source that is

of primary importance, we have found it necessary to use the term "colour appearance" every time we refer to the colour as could be expressed in the C.I.E. trichromatic co-ordinates.

The authors' simplified survey of the theory of phosphors should help many lighting engineers to understand what is happening inside lamps. It is interesting to note that in between the well defined line spectra from low-pressure electric discharges and the wide band spectra from normal phosphors we can see intermediate stages in the broadening lines of high-pressure discharges and the structure in the band spectra from certain phosphors such as magnesium arsenate and magnesium fluogermanate. Do the authors find, as we do, that phosphors showing this structure at room temperature generally maintain efficiency well at higher temperatures?

One of the main points in the study of electroluminescence may be the help that it gives to explaining what is happening inside phosphors. The authors mention that they have had some difficulty in obtaining a good maintenance of light output from such sources. We have found that this may be to some extent connected with the conductivity of the phosphor, and by special precautions we have had sources operating at a brightness of about 2½-ft. lamberts for some hundreds of hours without appreciable loss. I would, however, like to re-emphasise the points made regarding the major problems of low efficiency and convenience of form for obtaining any quantity of light from electric supply mains.

For lighting engineers the points concerning the application of the phosphors to lamps are of primary importance. As Mr. Jenkins mentioned, much of the work is covered by papers published in the period 1938 to 1943. One object of this Society must be the education of its younger members, and the survey covered in this paper should be most useful to them.

I would like to pay a tribute to Mr. McKeag and his colleagues in other companies whose painstaking work has made possible the wide uses of reliable phosphors in our modern lamps.

MR. W. HARRISON: My comments will be concerned with the efficiency and colour of the tubular fluorescent lamp. The authors give the figure of 65 lm./w. for the maximum efficiency likely to be achieved with the present type lamp. Does this figure refer to an equal energy spectral distribution? Assuming it does, I have made a rough calculation for the "Daylight" fluorescent spectral distribution and have obtained a value of 80 lm./w. It therefore appears that the limiting values of efficiency for fluorescent lamps are 80 lm./w. for a spectral distribution similar to that of the present "Daylight" fluorescent lamp and 60 lm./w. for a fairly flat spectral distribution having high colour quality. The present lamps achieve about two-thirds of these values.

We may then ask the question, "Is it worth while to sacrifice colour quality for high efficiency?" The authors refer to the trend both in this country and in the U.S.A. to make one lamp of high efficiency and one of good colour quality. I think it is a pity to make the former the one for general lighting service, and the better colour lamp the one for rather specialised use where colour is obviously of first importance. My view is that a flat efficiency maintenance and good colour quality are more important requirements than high efficiency for good lighting. I would suggest that good lighting needs good colour quality. Of course, the argument may be made that with the lower efficiency lamp 10 per cent. to 30 per cent. more lamps are required to obtain the same illumination, but it may well be that a lower level of illumination is acceptable with better colour quality, and who can measure the advantage of making the workers in an office or factory happier because the colour quality is right?

I think we might have the simulation of sunlight colour quality as an objective.

It is sometimes said that natural light is not attractive at low illumination levels but while this may be so out of doors we often have illumination levels of 10 to 20 lm./ft.^{2} indoors and find it entirely satisfactory. Referring to the equivalent colour temperatures quoted in the paper, that for the "Daylight" fluorescent lamp is 4,500 deg. K and for "Natural" 4,200 deg. K. The equivalent colour temperature for sunlight is approximately 5,500 deg. K, so as far as chromaticity is concerned, the "Daylight" and "Natural" fluorescent lamps are appreciably warmer.

I suggest that if we could make a lamp with chromaticity in the "Daylight"/"Natural" region and a spectral distribution very close to that of a full radiator, such a lamp would fulfil practically every lighting need.

MR. J. G. HOLMES: First, may I ask about the ultra-violet transformation lamps? They were both a pale blue colour and I would ask confirmation that this was visible light within the normal wavelength range and not that we were seeing the ultra-violet.

Secondly, a question about the high pressure MA. and MB. fluorescent lamps. These used to be made with a fine powder on the inside of a pearl bulb; nowadays they are made with a rather coarsely ground powder on the inside of a clear bulb, with the result that one can see the discharge itself in the middle of the bulb. When these lamps are used in beam-forming fittings such as a street lighting lantern, there is a high intensity beam of glaring blue light projected straight down the road, and the fluorescent orange-coloured light is merely diffused round the lamp-post itself. The colour correction is considerably distorted and it seems to me that there is considerable glare. I wonder if this is necessary and I suspect from some of the demonstrations we have seen that it is not going to be continued. I would appreciate some comments on whether this effect, which I think rather undesirable in present lamps, can be overcome, and if so, whether we can look forward to the improvement fairly soon.

MR. J. A. C. KING: I should like to refer to a remark made by one of the earlier speakers in the discussion when he said that we should work for a colour temperature similar to sunlight for ideal lighting sources. I think we need some specification of what we mean by "sunlight"; this is closely tied up with the question of the quality of colour rendering we require in different places. There are undoubtedly jobs in which the most natural colour rendering possible is needed, but there are many other jobs where an approximation to that colour rendering is much less satisfactory than something which makes no attempt to get close to that approximation. Examples are seen in restaurants with fluorescent installations in which the lamps are "warmer" than the ordinary warm white lamps and in which the red rendering is defective, making some foodstuffs appear unpalatable. It does seem that the tungsten filament lamp, although it definitely distorts colours, gives us a distortion which we have come to accept through long use and to which we are accustomed. I should like to put the question—"Until we can get a fluorescent lamp of really good colour rendering at a reasonable price for commercial use in large quantities, are we improving or are we spoiling the results by introducing something which is a closer approximation to daylight before we have something so close to it that there are no noticeable differences?" This is closely connected to the question of what sort of sunlight we are aiming at as the ideal light. Is it what we get from the sun on a bright summer day, what we get from the sun on a clear spring or autumn evening, or, what used to be regarded as the ideal for colour work, a good north aspect with no direct sunlight in it at all? Which is to be our standard? They are all acceptable, they all have their uses. The

places that want to use good lighting are, I think, often making things very much worse. If you see coloured fabrics under tungsten light you can judge their appearance, but if you see them under a modern fluorescent lamp you are never quite sure what you are seeing, because you are never quite sure what is in the light and what is in the colour of the fabrics. Seen under a high-intensity argon discharge you may get the necessary quality of colour rendering—is that within the bounds of possibility or are we never going to get that sort of colour rendering? Every time we see a new phosphor or new discharge lamp that is a better approximation to daylight we think it is good, but a month or two of working with it and we have found all sorts of disadvantages. Are we, with our advances in knowledge, throwing them out to commercial use too soon and so completely confusing the people who pay for the lighting installations?

MR. S. S. BEGGS: I would like to ask the authors whether the suggestion is that the new red phosphor would be applied to what is usually called the ordinary H.P.M.V. lamp. I believe the present lamp uses a cadmium-mercury tube and I gather that particular combination is used because of the rich ultra-violet radiation it produces. In that connection is the lack of coloration of the phosphor, i.e. the natural coloration, necessarily an advantage? I understand that the cadmium corrected discharge, although advantageous as regards the ultra-violet radiation, gave rather too much blue light and actually the yellow coloration of the powder was of advantage in helping to correct that excess. There might still be some advantage in not necessarily having a white powder for the phosphor.

I like the colour rendering of the fluorescent lamp imitating tungsten filament lamp light. Is there any hope of getting that at a reasonably high efficiency? I think there is a field for a really warm light of that kind.

In quoting the figure for maximum luminous efficiency (the "electrical equivalent of light") the authors are about 10 per cent. low on what is now quoted, based on the accepted values for the standard visual luminosity curve and the black body radiation curve for the basic standard source. I suggest the authors should correct the figure they quote.

DR. S. T. HENDERSON: I should like to say something about lamp efficiency. My experience is very similar to Mr. Harrison's, but I do not apologise for emphasising this subject because it is so important to lighting engineers. On the question of calculating maximum efficiency of a lamp I feel that the authors' figures are somewhat out of date. The electrical equivalent of light, already mentioned, is one of the relevant points; indeed, these particular calculations have lost their value and need revision. They give a maximum efficiency of 65 lm./w.; we have, in fact, obtained 65 lm./w. in experimental 4-ft. 40-watt lamps of near daylight colour, and it is quite clear on looking at the lamps that they have not yet reached their maximum efficiency. In the United States, moreover, manufacturers are regularly obtaining 65 lm./w. for their so-called "White" colour. I made some calculations based on the known spectral energy distribution of lamps and these calculations, like Mr. Harrison's, gave 80 lm./w. Thus we have a target which is worth aiming at. If we accept 65 lm./w. as the maximum there is not much more to be done.

The fallacies in the authors' calculations are, firstly, the electrical equivalent of light, which should be 680 instead of 620 lm./w.; secondly, they use some artificial daylight distribution which has a possible efficiency of only 230 lm./w., whereas normal phosphors in use to-day give 300-350 lm./w.. The third point is that there is an 80-90 per cent. correction put in for "quantum efficiency," and it seems that this factor covers several different effects. I do not know of any actual determination of quantum efficiency for a lamp phosphor but presume the true value may be nearer unity; the 80-90

per cent. factor, however, also includes effects due to imperfection of the coating, i.e. the loss of light by scattering, etc. That is a matter which we can hope to improve, and so in my calculations I omitted this factor. One other important detail—there is no mention of whether the authors allowed for the cathode drop in an actual lamp. In a 4-ft. 40-watt lamp we lose about 7 watts in cathode drop. Considering all these points we arrive at a possible efficiency of something like 80 lm./w. for a complete lamp, or 96 lm./w. for the positive column alone. This is, of course, not an exact calculation, and there are two features of it which I would urge should be considered by those working in this field; one is the 60 per cent. conversion of electrical energy to 2537 A. radiation. This is one of those "constants" which is passed on from one author to another without comment; it really should be redetermined under the conditions of present-day lamp operation. Then there is the presence of 1850 A. radiation which is usually ignored. This radiation is difficult to work with, but might well be a fruitful study; it is likely to excite all phosphors to some extent, and thereby improve the efficiency that we can expect.

MR. A. G. PENNY: Listening to the discussion I could not help noticing the difference between the lamp engineers and the lighting engineers. It seemed to me that the old brigade are still talking about lumens per watt and the new ones talking about colour.

Lighting engineers should not overlook the enormous importance of lumens per watt, as without the work of the lamp engineer in producing highly efficient light sources, the lighting engineer would still be struggling with inadequate light. The matter now becomes of greater importance in view of the rising cost of electricity.

Lamp engineers on the other hand seem to me to be in danger of falling into a trap in striving for the "ideal" colour or even for a "standard" general purpose colour. A standard must receive general acceptance and is only possible if the attitude of the majority of users is similar and unchanging. I think it is clear that users' ideas about colour are continually changing, in the sense that they are becoming more and more colour conscious. As a result, they become more and more willing to make sacrifices in other directions—even of efficiency—in order to get the colour they find most satisfactory.

The situation thus continually changes and what to-day might be considered a good colour, will to-morrow be thought inadequate. What is wanted is a wider realisation that the public demand for good colour is already ahead of manufacturers' achievement.

MR. J. LAWSON RUSSELL: I am always very interested in new suggestions for instrument lighting and I think there is some promise in electroluminescence.

I am wondering whether the authors have done any work on the possible production of a phosphor which will produce ultra violet so that we can still use fluorescent markings on the dial and activate from phosphor sources included in the instrument.

MR. E. R. HARRISON-JONES: On the question of fluorescent sources it is sometimes a desirable feature to make the colour similar to that of incandescent lamps. We have found the white very useful indeed, especially when dealing with commercial interiors, restaurants, etc., but this is known as the "3500 White" because of its colour appearance and we are finding that colour a very good answer where warm white or peach has been much too mauve or too blue.

MR. S. ANDERSON: I was a little surprised to see in the authors' table the various colours of fluorescent lamp on the market in this country and in the United States

given in terms of full radiator temperatures. I was under the impression that it was fairly well agreed that was not a very satisfactory method of comparison or specification and that we were going to use in future either the X—Y co-ordinating system or the C.I.E. eight-band system. Might I make a plea, to help those of us who are not familiar with these systems, that in the written paper the equivalent values for the lamps are given in these co-ordinating and eight-band systems, so that we have some sort of yardstick to know what the colours appear as in the various systems which are still apparently all partially used.

MR. H. G. JENKINS: We would like to thank all who took part in the discussion and others who listened so patiently to the paper.

Replying to Mr. Ruff, the purpose of the demonstration of fluorescent U.V. lamps was to illustrate the two main types of phosphor mentioned in Table 2. I agree with Mr. Ruff that the efficiency of the H.P.M.V. lamp as a producer of long-wave U.V. is lower than that of a U.V. fluorescent lamp. The convenience of the more intense H.P.M.V. source, however, and the ease with which it can be used optically, more than compensates for this in many applications.

I was not aware that we were in any way troubled by the question of what is the "colour" of a lamp, and can find nothing in our paper to suggest vagueness or confusion in this particular matter.

I do not think there is any relation between the appearance of structure in the emission bands of phosphors and their temperature stability as suggested by Mr. Ruff. Calcium tungstate activated by samarium shows structure in its emission spectrum but does not maintain efficiency well at higher temperatures. Strontium-silicate activated by divalent europium shows no structure in its emission spectrum, but is still luminescent above 400 deg. C.

Mr. Harrison raised some important questions which were subsequently elaborated by Dr. Henderson. The purpose of our, admittedly rough, calculation of the maximum efficiency was to show the various factors which had to be considered in such an estimate and to indicate that we had already gone a long way to achieving the maximum. I accept Mr. Harrison's figure of 80 lm./w. for a spectral distribution similar to that of the present "Daylight" lamp; our calculation referred to a high colour quality distribution approximating to that of true daylight.

I believe, with Mr. Harrison, that there is a growing realisation of the importance of really good colour rendering and that it is well worth while sacrificing lumens per watt to achieve this. The present practice of offering the user a choice is, however, sensible and it may be that in the course of time the demand will go in the direction of colour rendering rather than high luminous efficiency.

I do not think it will ever be possible to satisfy all users by offering a single colour of sunlight quality as suggested by Mr. Harrison. My own views are that a range of colours is inevitable for some time to come, that colours of the "Daylight" or "Natural" type will continue to be used mainly for commercial and industrial applications at increasing levels of illumination and that "Mellow" or perhaps an even warmer colour of tungsten lamp quality, similar to that demonstrated this evening, will be increasingly used for restaurant, domestic and general recreational lighting at more normal illumination levels.

Replying to Mr. Holmes's questions. The U.V. radiation from the fluorescent U.V. lamps which we demonstrated is accompanied by some violet fluorescent light from the phosphor as well as by the visible light from the mercury discharge, which are responsible for the blue colour of the lamps demonstrated.

Mr. Holmes's second point is of considerable interest. I have always understood that the fluorescent coating on H.P.M.V. lamps should, preferably, transmit a certain amount of direct radiation from the discharge to enable the lamp to be used efficiently

in optical street lighting fittings. On the face of it, it seems advantageous to direct the discharge light along the road and to concentrate the corrected light on the road in the vicinity of the fitting. It was possible to do this with the older type of fluorescent lamp because of the large crystal size of the phosphor used, but with the newer, much smaller particle-size powders, it may not be possible. However, Mr. Holmes's remarks suggest that the matter is far from resolved by illuminating engineers and that a lamp in which the light from the arc tube is completely diffused by the fluorescent coating may prove to be acceptable.

I think we must sympathise with Mr. King's remarks since many of us are familiar with the unappetising appearance of food in restaurants where fluorescent lighting is used indiscriminately. As mentioned in my reply to Mr. Harrison, I consider that a warm colour of the "Mellow" type, or something even warmer, is desirable for this kind of lighting.

I agree with Mr. King that the appeal that tungsten lighting has for most of us is probably ingrained in us and part of our make-up. We have tried to show this evening that it is possible to produce a fluorescent lamp with colour characteristics very similar to tungsten sources and at an efficiency which, if well below the 80 lm./w. we have been hearing about to-night, is still high compared with that of the corresponding tungsten lamp.

Replying to the point raised by Mr. Beggs, the present 400-watt H.P.M.V. fluorescent lamp, which was first marketed in this country in mid-1930, uses a discharge through mercury and cadmium vapour partly because the strong blue cadmium lines counteract to some extent the loss of the mercury blue radiation by absorption in the yellowish phosphor, and partly because cadmium also emits strong red radiation which supplements that from the phosphor.

For various reasons cadmium cannot readily be used in 80-watt and 125-watt quartz lamps and these ratings of fluorescent lamp are not corrected in this way. The new red phosphors have not only a much higher red light output than those used in the early lamp, but because of their lack of self colour they give the fluorescent lamp a pleasant white appearance when alight.

I am glad to note Mr. Beggs's interest in fluorescent lamps with colour characteristics similar to those of tungsten lamps, and as he will have gathered from my remarks to other speakers, I agree with him that there is a field for a lamp of this kind.

I think I have already dealt with the main point raised by Dr. Henderson on our calculation of the maximum efficiency in my reply to Mr. Harrison. In a calculation of this kind one is, I think, justified in using a high-colour quality distribution approximating to that of a phase of ordinary daylight rather than some arbitrary distribution of the kind mentioned by Dr. Henderson, which has little resemblance to true daylight. Bearing this in mind, therefore, it will be clear that Dr. Henderson still has something worth while to aim at, for as Mr. Harrison points out, fluorescent lamps closest in spectral energy distribution to that of true daylight achieve only about two-thirds of this value.

Although not specifically mentioned in the paper, the calculation refers to a 4-ft. 40-watt lamp. It is, I believe, made clear in the paper that the 1850 A. and 2537 A. energies have been lumped together for the purpose of the rough calculation. Our quantum efficiency factor was taken to include all losses in the phosphor including scattering and losses due to absorption of visible light. I suggest that our rough calculation is at least realistic and that Dr. Henderson's, based on his own arbitrary choice of spectral energy distribution, tends to confuse the issue. We naturally agree with Dr. Henderson on the desirability of further and more accurate measurements of all the characteristics discussed, but these are hardly likely to effect our main conclusion.

Mr. Penny's remarks suggest that he is perched precariously on the fence between

high efficiency and good colour rendering. Lamp engineers, I think, strive to provide what is required, limited only by what is possible and reasonable. Mr. Penny's statement that the public demand for good colours is already ahead of manufacturers' achievement ignores the simple fact that fluorescent lamps can now be made with colour characteristics indistinguishable from those of true daylight on the one hand and tungsten filament lamps on the other.

Replying to Mr. Russell, we have never succeeded in making an electroluminescent phosphor which emits in the U.V. and we are not aware that anyone else has succeeded in doing this. I am, however, interested in Mr. Russell's suggestion and we shall bear it in mind in our further work on electroluminescence.

I think the questions asked by Mr. Anderson have already been dealt with in a paper by Winch mentioned on the text (Reference 16). Figure 9 of the present paper gives the chromaticity co-ordinates of the main fluorescent lamp colours, together with those of a full radiator at various temperatures. I can only add that it was far from our intention to name fluorescent lamp colours in terms of full radiator temperatures and reference to Table 3 will, I hope, reveal that we have not done so.

Mr. Harrison-Jones mentions that the American colour known as "3,500 deg. White," which is still widely used in the U.S.A., has found application over here for commercial interiors, restaurants, etc. I agree that this is an excellent colour for many lighting jobs and a similar colour under the name "Intermediate White" has been used for several years past in some cold cathode lamps. My own view is that it is hardly the correct colour for restaurant lighting.

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With a view to avoiding possible confusion with other publications, reference to these Transactions should be in the form :—"Trans. Illum. Eng. Soc. (London)."

The Properties of White Rigid Polyvinyl Chloride Sheet

By W. E. HARPER, B.Sc. (Eng.), Ph.D., A.M.I.E.E., *(Member)*.

Summary

An opaque white grade of rigid polyvinyl chloride sheet has been developed* for use as a diffusely reflecting material and this paper reports the results of photometric, thermal, mechanical and ageing tests made on production sheet. The tests show rigid p.v.c. to have the properties required of a highly efficient reflecting material; the thermal characteristics, however, limit use to fittings in which the temperature of the shapings is not greater than 55 deg. C.

(1) Introduction

One of the most important uses of plastics in lighting fittings is that of opal acrylic sheet for translucent reflectors(1). Widely used for both industrial and commercial lighting, acrylic reflectors have contributed notably towards achieving the brightness gradations of both fitting and surround required by modern lighting techniques. In some installations, however, upward lighting is unnecessary, and there has been a demand for an opaque plastic reflecting material having properties at least equal to those of competitive materials and lower in cost than acrylic sheet.

Trials with a number of synthetic plastics showed unplasticised rigid polyvinyl chloride (p.v.c.) sheet to have the best balance of properties, and development was concentrated on producing a suitable grade of this material. In its natural form, rigid p.v.c. is a transparent, straw-coloured polymer with a refractive index of 1.54; by incorporating suitable pigments the natural polymer can be modified to give an opaque white grade with the required optical characteristics.

The composition is first calendered to produce a white foil, and layers of the foil are then laminated under heat and pressure to form sheets 6 ft. x 4 ft. in area. Intended primarily for use in fluorescent lamp industrial reflectors, white rigid p.v.c. is remarkably strong, and as satisfactory shapings can be formed from 1/16 in. sheet this thickness has been standardised for lighting fitting material.

The performance of white p.v.c. relative to its use in lighting equipment has been evaluated, and this paper reports the results of photometric, thermal, mechanical and ageing tests. For the experimental work all specimens were taken from production sheets selected at random from stock.

(2) Optical Properties

Compared with opal acrylic sheet white p.v.c. is slightly cream in colour, and this difference is shown quantitatively by the values of the chromaticity co-ordinates of the two materials given in Table 1; values for a "true white" are added for reference. Measurements were made on twelve specimens of p.v.c. using a Donaldson Six-Stimuli Colorimeter(2) with Standard Illuminant A as source. Variation in colour between the samples was very small and less than the errors of measurement.

As the most important use of white p.v.c. is likely to be in fittings equipped with fluorescent lamps, the reflection factor of the material was measured with Standard Illuminant B in addition to the more usual measurement with Standard Illuminant A, the former source having colour characteristics similar to those of "daylight quality" fluorescent lamps(3). Measurements were made with parallel light using Waldram's

Dr. Harper is with Imperial Chemical Industries, Ltd., Plastics Division.

* The data in this paper refer to the white rigid polyvinyl chloride sheet manufactured by Imperial Chemical Industries, Ltd. Similar material produced by other manufacturers may have somewhat different properties.

Table 1
Colour of White Rigid P.V.C. Sheet.

Material	Number of specimens	Source	Chromaticity co-ordinates		
			x	*y*	*z*
White rigid p.v.c.	12	Std. Ill. A	0.460	0.409	0.131
Opal acrylic sheet	—	,,	0.451	0.407	0.142
" True White "	—	,,	0.448	0.407	0.145

apparatus([4]) which was, however, modified to obtain greater speed and ease of operation([5]).

The results of these reflection factor measurements (Table 2) show that white rigid p.v.c. has a very high reflection factor to light from both sources, and that the variation between samples is negligible. Although the change in mean reflection factor corresponding to change in source is small, it is statistically significant and agrees in trend with the colorimetric measurements.

Being a press-laminated material, the surface finish of p.v.c. sheet is determined by the surface finish of the pressing plates. Polished plates are used for present production and give sheets showing mixed specular and diffuse reflection.

The experimental curve of Fig. 1 was derived from measurements of the specular reflection at different angles of incidence. Comparison with the theoretical curve calculated for a material of refractive index 1.54([6]) indicates that over the range of the experiment there is little difference between the specular reflection factor of the test sample and that of an ideal polished surface. When designing fittings where the specular component is important, the error incurred by assuming the sheets to have perfectly polished surfaces is therefore negligible.

Values of specular reflection alone, however, are seldom sufficient to describe the surface finish of mixed reflectors([7]); in particular, they give little appreciation of the " appearance " of a surface. Although the reflection factor of p.v.c. sheet is close to that of the ideal polished surface, the appearance when viewed at angles near to the normal is less " clean " than that of such materials as polished plate glass and cast acrylic sheet, owing to reproduction of the press plate polishing marks on the p.v.c. sheet. This difference in appearance does not, however, affect the performance of the material.

(3) Thermal Properties

The most important thermal property of any thermoplastic used in lighting fittings is the maximum temperature at which a shaping can operate for long periods of time without significant distortion. P. H. Collins and the present author developed an apparatus for measuring demoulding-time curves for acrylic shapings operating at a constant raised temperature, and showed from the form of the curves that the total

Table 2
Reflection Factor of White Rigid P.V.C. Sheet with Normally Incident Parallel Light.

Source	Number of specimens	Reflection factor	
		Mean	Standard deviation
Standard Illuminant A	20	0.861	0.006
Standard Illuminant B	20	0.852	0.005

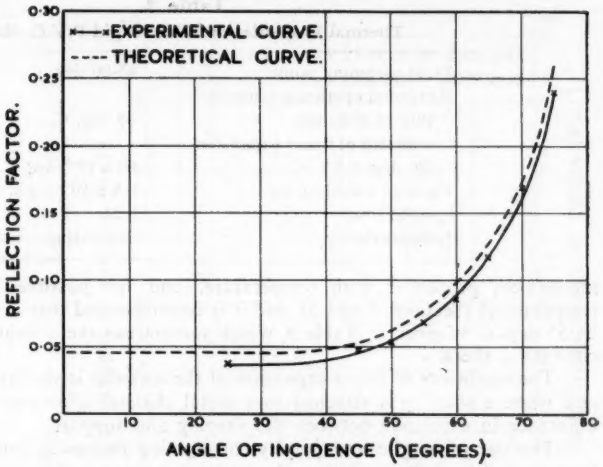

Fig. 1. Specular reflection from surface of white rigid p.v.c. sheet.

demoulding during a service life of several years is unlikely to exceed 0.1 in. provided that the cumulative demoulding after 100 minutes is less than 0.020 in. under the specified test conditions([8]). Demoulding-time curves were determined for groups of five 8 in. diameter hemispheres blown from 1/16 in. rigid p.v.c.; they have the same form as the curves obtained previously for acrylic hemispheres, indicating that the demoulding process is similar for both materials. The relationship between the average cumulative demoulding after 100 minutes and temperature (Fig. 2) suggests that the maximum operating temperature for p.v.c. shapings is approximately 65 deg. C. Allowance must, however, be made for variations in the material, for change in

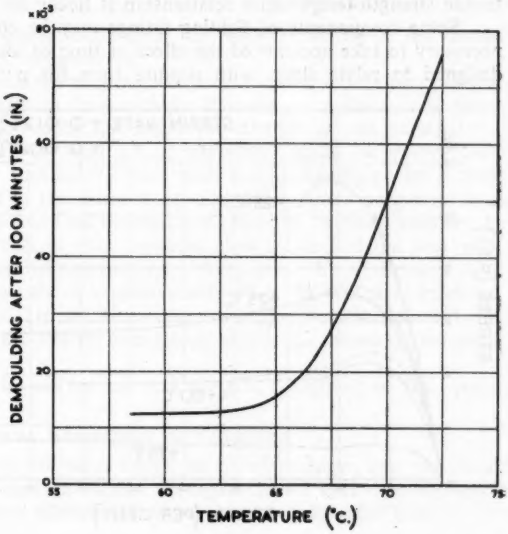

Fig. 2. Variation in demoulding after 100 minutes of rigid p.v.c. hemispheres with temperature.

Table 3
Thermal Properties of White Rigid P.V.C. Sheet.

Vicat softening point	85-90 deg. C.
Maximum operating temperature of shapings	55 deg. C.
Co-efficient of linear expansion (20 deg. C.)	80×10^{-6}/deg. C.
Thermal conductivity	3.5×10^{-4} c.g.s. units
Specific heat	0.24
Inflammability	Self-extinguishing

mechanical properties with temperature, and for possible discoloration at raised temperatures (Sections 4 and 5), and it is recommended that in practice the upper limit be 55 deg. C as given in Table 3, which summarises the relevant thermal properties of rigid p.v.c. sheet.

The coefficient of linear expansion of the material is similar to that of acrylic sheet, and when a shaping is attached to a metal channel allowance must be made for the difference in expansion between the shaping and support.

The use of acrylic and polystyrene lighting fittings in some public buildings has been limited by inflammability. In contrast, p.v.c. is self-extinguishing.

(4) Mechanical Properties

Rigid p.v.c. has good mechanical properties with outstanding impact strength. In common with other thermoplastics, some properties of the material are both time and temperature dependent, the strength in general falling with increase in time of loading and with rise in temperature.

Fig. 3 shows typical strain-stress curves of rigid p.v.c. determined for two straining rates and four temperatures, and Fig. 4 the variations in stress at failure and tangent modulus with temperature. Over the working temperature range of the material the tensile strength-temperature relationship is linear for short period testing rates.

Some components of lighting fittings may be continuously loaded, and it is then necessary to take account of the effect of time of loading on strength[9]. Experiments designed to relate stress with rupture time for p.v.c. show that the relationship is

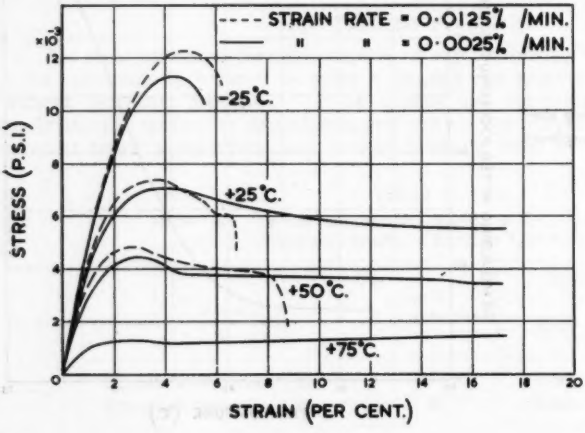

Fig. 3. Stress-strain curves for rigid p.v.c. sheet.

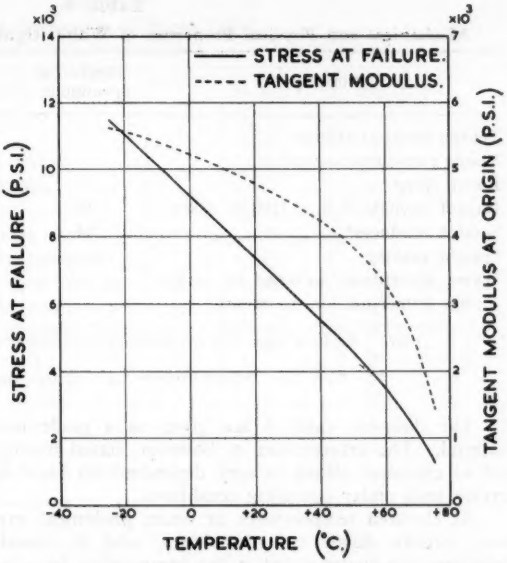

Fig. 4. Variation in mechanical properties of rigid p.v.c. sheet with temperature.

approximately logarithmic over a period of 1,000-2,000 hours, with a strength at the end of the period about one-third of that determined by the short time tests. It appears, however, that the rupture stress of p.v.c. reaches a limiting value at times of this order, and that thereafter continuous loading can be sustained indefinitely without failure. From the data available a safe working stress for continuously loaded components is obtained by applying a factor of safety of 4 to the short-time tensile test values given in Fig. 4.

The compression and shear strengths of p.v.c. are directly related to the tensile strength by factors of 1.2 and 0.75 respectively.

All the strength values given assume that the component is free from sharp notches or corners and from abrupt changes in cross-section; if these are present local stress concentration will result, and will reduce the long-term strength of the material.

To assess the impact strength of rigid p.v.c., tests were made on twelve 5-in. diameter discs using a pendulum machine[8] fitted with a 6-lb. hammer with a 1-in. diameter hardened steel nose. The test discs were clamped at their periphery to a $\frac{1}{2}$-in. wide steel ring bolted to the anvil of the machine, and the hammer adjusted to strike the discs normally at their centre. The repeated blow method of test was used, and the results can be considered as equivalent to those given by a simple falling weight machine. At a hammer energy of approximately 70 in. lb. the discs indented, but for fracture a mean energy of 116 in. lb was necessary. It is estimated that this value is more than twenty times the impact strength of acrylic specimens of the same dimensions.

Data derived from tests of the mechanical and physical properties of rigid p.v.c. are given in Table 4.

(5) Chemical Resistance and Ageing

Rigid p.v.c. is very resistant to chemical attack by many reagents, and one of its most important uses may be in lighting fittings for operation in corrosive industrial atmospheres where enamelled metal fittings fail in a comparatively short time.

Table 4

Mechanical and Physical Properties of White Rigid P.V.C. Sheet at 20 deg. C.

Property	Number of specimens	Mean value	Standard deviation
Tensile stress at failure	—	7400 p.s.i.	—
Young's modulus in bend	—	4.6×10^5 p.s.i.	—
Punch shear	—	9000 p.s.i.	—
Impact strength 5 in. x 1/16 in. discs.	12	116 in. lb.	9
Scratch hardness*	14	19.1	0.1
Specific gravity	—	1.39	—
Water absorption—increase in weight after immersion for one month	—	0.19 per cent.	—

* Scratch hardness values were determined by a pyramid scratch test using a 2 kgm. load.

$$\text{Scratch hardness} = \frac{1}{\text{Scratch width in cm.}}$$

The data of Table 5 are given as a guide to the chemical resistance of the material. The information is, however, based mainly on chemical plant experience, and as chemical attack is very dependent on local factors it is often wise to make service tests under operating conditions.

At elevated temperatures or under prolonged exposure to sunlight, natural rigid p.v.c. breaks down and discolours, and to counteract this degradation colour stabilisers are incorporated in the composition from which the white sheets are made. The efficacy of these stabilisers has been assessed by two tests.

In the first test, specimens were illuminated uniformly by light from " 4,500 deg. K Daylight " fluorescent lamps. The test was continuous and the distance between the specimens and the lamps was adjusted from time to time to maintain an illumination at the specimens of 300 lm./ft.^{2}. After approximately 5,000 hours exposure, the colour and reflection factor of the specimens and of control samples were measured to give the results of Table 6. These show that bleaching has occurred, with small but significant increases in reflection factor; the changes are readily seen by inspection.

For determining the change in optical properties caused by operation at raised temperatures, a second group of specimens was mounted in a convection oven, thermostatically controlled at 60 deg. C. Photometric measurements made on these samples after 4,000 hours' operation (Table 7) showed that some discoloration had taken place. In practice this thermal degradation will be reduced by the bleaching action of the light and by limiting the operating temperature to 55 deg. C. as recommended in Section 3.

Both groups of specimens were examined after a further 2,500 hours' operation. No further change in optical properties could be observed by visual inspection, and it would seem that the recorded changes may well occur rapidly, the rate of change decreasing progressively with time. Work to establish this relationship is in progress.

These laboratory ageing tests have been supplemented by tests on fluorescent lamp reflectors operating in normal service at four locations:

(i) An office in a district with reasonably clean atmosphere;
(ii) An iron and steel foundry;
(iii) An electrolytic cell room in the chlorine plant of a chemical factory;
(iv) Over filter presses in a dye works.

After approximately six months' operation the only noticeable change was the slight bleaching referred to above. Enamelled steel reflectors erected as controls failed in locations (ii) and (iv) after two months' operation. At location (iv) where a vitreous

Table 5

Chemical Resistance of Rigid P.V.C.

S=Satisfactory; A=Some attack or absorption; U=Unsatisfactory.

Agent	20 deg. C.	60 deg. C.
Acetone	U	—
Ammonia—100 per cent dry gas	S	S
Ammonium hydroxide (0.880)	S	S
Benzene	U	—
Butyl alcohol—100 per cent	S	A
Calcium chloride (saturated solution)	S	S
Carbon dioxide—100 per cent. dry gas	S	S
,, ,, —any concentration wet	S	A
Chlorine—100 per cent. dry gas	S	A
Glycerine	S	S
Hydrochloric acid—10 per cent.	S	S
,, ,, —35 per cent.	S	S
Hydrofluoric acid—40 per cent.	S	A
Hydrogen—100 per cent.	S	S
Mineral oils	S	S
Nitric acid—10 per cent.	S	S
,, ,, —98 per cent.	U	—
Oxygen—100 per cent.	S	S
Ozone—100 per cent.	S	—
Petrol—100 per cent.	S	S
Petrol-benzene mixture—80/20	U	—
Phosphoric acid—90 per cent.	S	S
Potassium hydroxide solution	S	S
Propane liquid and gas	S	—
Sea water	S	S
Soap solution—any concentration	S	S
Sodium chloride	S	S
Sodium hydroxide	S	S
Sulphur dioxide—100 per cent. dry gas	S	S
,, ,, —100 per cent. moist gas	S	A
Sulphuric acid—up to 90 per cent.	S	S
,, ,, —98 per cent.	S	A
Trichlorethylene	U	—
Vegetable oils and fats	S	S

Table 6

Ageing of White Rigid P.V.C. Sheet Exposed to Light from Fluorescent Lamps.

Test source	Specimen	Number of specimens	Illumination	Test period	Reflection factor		Chromaticity		
					Mean	Standard deviation	x	y	z
			lm./ft.^{2}	hours					
Std. Ill.A	Control	6	—	—	0.857	0.005	0.460	0.409	0.131
	Test	6	300	5280	0.864	0.003	0.455	0.408	0.137
Std. Ill.B	Control	6	—	—	0.851	0.003	—	—	—
	Test	6	300	5280	0.864	0.003	—	—	—

Table 7

Ageing of White Rigid P.V.C. Sheet at Elevated Temperature.

Test source	Specimen	Number of specimens	Temperature of test	Test period	Reflection factor		Chromaticity		
					Mean	Standard deviation	x	y	z
			deg. C.	hours					
Std. Ill.A	Control	6	—	—	0.861	0.005	0.460	0.409	0.131
	Test	6	60	4200	0.813	0.004	0.466	0.409	0.125
Std. Ill.B	Control	6	—	—	0.854	0.005	—	—	—
	Test	6	60	4200	0.810	0.001	—	—	—

enamelled reflector was the control, corrosion was so severe that breakdown was general and at one point on the reflector a hole had formed in the metal.

Although these ageing tests are not yet completed, from the laboratory and service data now available it is reasonable to conclude that the only change probable in the photometric performance of p.v.c. reflectors operating with fluorescent lamps will be a slight improvement consequent on the photochemical bleaching of the polymer. There is no indication that the performance will be adversely affected by chemical attack, even in highly corrosive atmospheres.

(6) Shaping and Fabrication

Rigid p.v.c. sheet can be shaped by any of the established thermoplastic sheet techniques. Prior to shaping, blanks should be uniformly heated for 10-12 minutes at 120 deg. C. plus or minus 5 deg. C.; the material stiffens rapidly on cooling, so shaping should be completed as quickly as possible after the blank has been removed from the oven. Where metal moulds are used, they should be warmed to avoid chilling the heated material.

Double curvature shaping requires forming pressures higher than those necessary with most other thermoplastics, and allowance must be made for this both in design of the tools and when determining the most suitable shaping technique. In general, pressing is the most useful method of forming rigid p.v.c. sheet.

The material can be readily machined by standard methods, cold-bent and cold-blanked, and can be jointed either by cementing or by welding. It can also be cemented to metals and other materials.

(7) Design Data

From the data given in the preceding sections it is possible to derive some principles of design for p.v.c. fittings.

(i) Although the material is remarkably tough, the sheets are thin and shapings will consequently be somewhat flexible. This slight flexibility enables the shapings to withstand damage from rough handling but, if desired, they can be stiffened by incorporating ribs which can be moulded into the shaping; free edges to reflectors should be avoided, return edges or moulded flanges being used where possible. It is also necessary that the points of support should be correctly positioned to eliminate risk of sagging.

(ii) To overcome the consequences of notch sensitivity, generous radii at corners should be used and the material should not be overloaded locally at fixing holes or slots

(iii) Fittings should be so designed that no part of a shaping operates continuously

at a temperature exceeding 55 deg. C. With fluorescent lamp fittings, over-heating is most likely to occur in the neighbourhood of the electrodes, and metal electrode shields may be necessary. For the same reason it is also advisable to separate the p.v.c. shapings from the control-gear enclosure by suitable spacers.

(iv) Adequate allowance must be made for expansion. If a shaping is fastened rigidly to a metal channel or housing and the temperature rise of the unit is 30 deg. C., the stresses in the p.v.c. consequent on the differential expansion of the two materials will exceed the maximum stress permitted for safe operation at 55 deg. C.

(v) Where a welded construction is used, a weld strength of 70 per cent. of the sheet strength is possible if the operators are skilled, but in practice it is advisable to reduce this to 50 per cent. of the sheet strength to allow for defective workmanship.

(vi) Finally, it is necessary for the designer to choose dimensions for his fittings such that the blanks can be cut from sheets of standard size without cutting losses. When computing blank sizes it is necessary to allow approximately 1 per cent. for shrinkage during heating, and where shapings are to be formed by pressing or blowing techniques a clamping flange $\frac{1}{2}$ in. to 1 in. wide will be necessary.

(8) Conclusions

White rigid p.v.c. sheet is a diffusely reflecting material with a high initial reflection factor, which is maintained under arduous service conditions. Like the acrylic plastics its properties are very consistent and the variation between material drawn from different batches is negligible.

Although it may find application in many types of lighting equipment, the permanence and strength of p.v.c. make it particularly suitable for use in fittings designed to operate in bad industrial locations.

Shapings made from the sheet are characterised by toughness allied to a measure of flexibility, making them almost immune to damage during handling, packing and storing.

For satisfactory performance the temperature of p.v.c. shapings should not exceed 55 deg. C., a condition which may largely limit use to fluorescent lamp fittings. In addition to the white opaque material whose properties have been reviewed in this paper, rigid p.v.c. sheet is available in black and in a number of colours. Coloured and white foils can be laminated together to produce sheets white on one side and coloured on the other. Further developments are in progress which may lead to the production of translucent reflecting and diffusing grades.

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